# Autonomous Robot Navigation Using Advanced Motion Primitives

Mihail Pivtoraiko, Issa A.D. Nesnas
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
{mpivtora, nesnas}@ jpl.nasa.gov

Alonzo Kelly
Robotics Institute
Carnegie Mellon University
5000 Forbes Ave.
Pittsburgh, PA 15213
alonzo@cmu.edu

*Abstract*—We present an approach to efficient navigation of autonomous wheeled robots, operating in cluttered natural environments. The approach builds upon a popular method of autonomous robot navigation, where desired robot motions are computed using local and global motion planners operating in tandem. A conventional approach to designing the local planner in this setting is to evaluate a certain number of constant-curvature arc motions and pick one that is the best balance between the quality of obstacle avoidance and minimizing traversed path length to the goal (or a similar measure of operation cost). The presented approach proposes a different set of motion alternatives considered by the local planner. Important performance improvement is achieved by relaxing the assumption that motion alternatives are constant-curvature arcs. We first present a method to measure the quality of local planners in this setting. Further, we identify general techniques of designing improved sets of motion alternatives. By virtue of a minor modification, solely replacing the motions considered by the local planner, our approach offers a measurable performance improvement of dual-planner navigation systems[1,2].

**TABLE OF CONTENTS**



## 1. INTRODUCTION

Autonomous rover navigation is an enabling technology for space exploration. It offers a number of significant benefits:

- Lower cost and effort for mission management,
- Increased scientific return,
- Efficient multi-robot coordination for exploration or construction of habitats,
- Improved motion quality when teleoperation is infeasible or impractical.

Experience from the recent Mars Exploration Rover (MER) mission shows that significant improvements in rover autonomy, including navigation, are necessary. Severe environmental hazards, such as significant wheel slip and dense obstacle fields, make autonomy difficult. The autonomous rover navigation problem is a difficult problem because the terrain can be arbitrary, dynamics can be challenging, perceptual horizons and computational resources are typically limited, and motion efficiency with respect to time and energy expenditure must be considered.

This paper describes a method to achieve an incremental improvement of robot navigation efficiency over the popular approaches that feature dual (local and global) motion planners operating in tandem. Such an approach is currently in use by the Spirit and Opportunity rovers in the Mars Exploration Rovers mission. These and similar rovers can benefit from the proposed improvement as well. At no additional computational cost, by solely modifying the motion alternatives considered by the navigation system, the performance improvement was measured as the reduction of distance traveled towards a goal in rough terrain, duration of travel, and energy expenditure. The paper first develops the performance measures for autonomous navigation, based on its relevant qualities. Further, the measures are used to evaluate a number of approaches to designing the motion alternatives for the local planner. Finally, we report the quantitative improvement of rover navigation that was attained and detail the developed general principles of generating good motion alternatives for navigation.

## 2. PRIOR WORK

The topic of autonomous robot navigation in natural environments has received considerable attention. One of the early successful approaches proposed a dual hierarchy of motion planning, where a global planner provided the general direction toward the goal, and the local planner was responsible for determining the immediate motion of the robot [10]. Unlike terrestrial applications of this method,

1
[1] 978-1-4244-2622-5/09/$25.00 ©2009 IEEE.
[2] IEEEAC paper #1650, Version 1, Updated November 2, 2008.

where selecting a robot motion is repeated frequently, here we accommodate the computation and power limitations of space robotics. Due to such limitations, robot motion is computed less frequently. Therefore, a rover must commit to executing longer paths, in order to maintain efficiency of travel between the infrequent planning computations. In this paper, we make the assumption, common in navigating modern Mars rovers, that the rover executes the entire local plan (typically an arc path) before generating a new local plan.

A number of improvements to dual-planner navigation technique have been proposed [5][9], yet the overall dual planner concept is still widely used today. A similar approach was successfully applied to planetary rover navigation [2]. The contribution of this work is in identifying and relaxing an assumption of most applications of this navigation method regarding the local planner component. By virtue of generalizing the motions that are considered by it, navigation performance is improved, especially in complex and cluttered environments.

Other efforts have considered diversifying the motion alternatives used for local planning. In [6], an experimental study was undertaken that demonstrated significant benefits of departing from constant-curvature assumptions on local planner motions. Our work has confirmed the conjecture of that effort in the context of robot navigation with limited perception. Furthermore, we defined performance measures that are more closely related to navigation in outdoor environments. This work is also similar to [3], although we focus on finding motion alternatives that are most similar to the motions typically used, in order to maximize compatibility with the existing autonomous rover navigation systems.

## 3. Performance Measures of Motion Primitives

**Figure 1.** FIDO research rover prototype autonomously traverses rough terrain at Caltech Jet Propulsion Laboratory Mars Yard.

In order to orient the development of improved rover navigation, the performance of the state-of-the-art dual-planner approach was studied and evaluated. The GESTALT navigation system [2] was chosen as a representative solution for modern autonomous planetary navigation because it is currently utilized by the NASA Mars Exploration Rovers (MER), In order to evaluate new approaches to rover navigation, a system of rigorous and quantitative measurement of navigation quality had to be put in place.

To devise this system, extensive field experimentation with rover navigation using research rover prototypes in rough terrain at the California Institute of Technology (Caltech) Jet Propulsion Laboratory Mars Yard (Figure 1) was undertaken. From that experience, the quantitative measures of navigation quality were developed. Four relevant measures that were best suited for comparing navigation approaches are outlined below.

- Success or failure to reach the goal,
- Distance traveled,
- Time duration of travel,
- Energy expenditure.

These quantities were very well suited for evaluating navigation because they are accessible for direct measurement, well defined in the context of autonomous rover navigation and reflect the practical concerns of rover autonomy for planetary exploration. Both the actual rover and simulator software were instrumented to record the values of these measures during navigation in a consistent manner, in order to make comparison meaningful. The first (success/failure) measure was a boolean value, while SI units were used for other measures. Energy expenditure of the actual rover was derived from the measurement of electric current that was applied to the rover's motors during driving, while in simulation, an estimate of it was produced using available data. This estimate was calibrated by comparing with the data recorded using the actual rover.

## 4. Designing Motion Primitives for Rover Navigation

Once the relevant measures of navigation performance were developed, they were used to compare alternative approaches to rover navigation. All alternatives shared the same architecture as GESTALT: they consisted of two motion planners working in tandem [2]. A local planner evaluates a set of motion alternatives and suggests the best one to follow, and a global planner suggests the general direction toward the goal. The focus of this work has been to develop alternative navigator designs by solely modifying the local planner component of the system. Moreover, this modification was constrained to preserve the local planner approach of evaluating a small set of motion alternatives and picking the solution that minimizes a cost measure. The assumption of constant curvature arcs was relaxed in this work. In particular, we found notable performance improvement by considering variable curvature motion primitives in addition to arcs.

A number of general approaches to motion primitive design have been developed. It was verified experimentally that solely by replacing the constant curvature arcs in the local planner with the primitives presented below, it was possible to achieve a significant improvement of navigation performance. This improvement incurs no additional cost in runtime or memory storage, since solely replacing motion alternatives preserves the amount of computation.

*Motion Alternatives with Constant Curvature*

Since the GESTALT navigation system was used as the baseline in this work, all performance results below are quoted as ratios to the corresponding quantities as produced by executing GESTALT in the same experiment. For evaluation, the algorithm was implemented by following the available information from publications [1][2][7]. The representative set of 23 arcs used in GESTALT is depicted in Figure 2. Note that, for clarity, the figure shows only the forward arcs and omits the representations of point turns and backwards motions. To maintain the quality of comparison, all experiments used the same implementation of the rover navigation system. The only difference was the set of motion alternatives used by the local planner. These were made available as data files, such that no modification to software was necessary. The following subsections describe the general principles of designing good sets of motion alternatives, first by restricting motions to arcs, and then by allowing other types of paths with variable curvature.

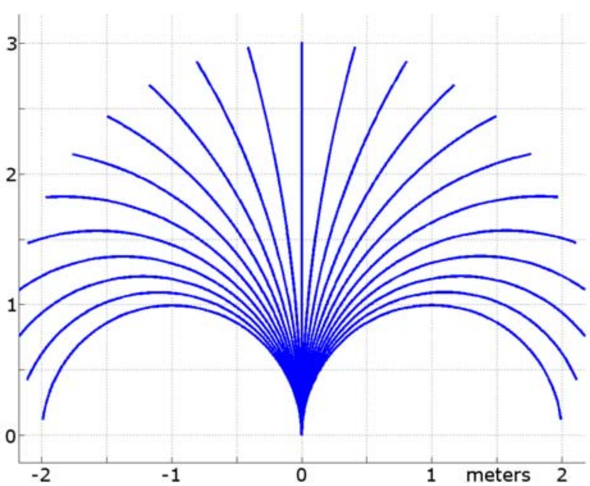


**Figure 2.** A set of 23 constant curvature arcs, similar to those used as motion alternatives by the GESTALT navigator [2].

*Improving Arc Motion Alternatives*

A set of motion alternatives that are constrained to arcs has a number of parameters that determine the paths in it. An arc can be viewed as a sample in two-dimensional space consisting of curvature and length (or, equivalently, heading change). Thus, the parameters of a set of equally-spaced arcs primarily include:

- Number of arcs,
- Maximum curvature,
- Maximum arc length.

Arc length is often interpreted as heading change of an arc. Also, the manner of sampling curvature and arc length, if not uniform, is an important parameter of a set of motion alternatives. In experimental work, we noted a number of general design principles for improving the performance measures of navigation systems equipped with sets of arcs. These principles are summarized in Table 1. Some of the parameters exhibit trade-offs between different navigation qualities. Such trade-offs are also noted in the table, along with suggestions on navigation scenarios that would benefit from values on either side of the trade-off.

An example of a set of arc motion alternatives that was developed using these guiding principles and verified experimentally is shown in Figure 3. For better comparison with the baseline system (Figure 2), as many parameters as possible remained the same, in particular the number of motions and the maximum curvature. Once again, only forward arcs are presented and point turns are omitted. A plot on the bottom in Figure 3 presents the results of the experimental comparison of this arc set vs. the baseline.

Both navigator variants traversed an environment consisting of point obstacles independently and identically distributed with approximate likelihood 1%. The navigation goal was randomly chosen approximately 20 meters from the initial rover position. A realistic limited perception horizon was used with the field of view ±40º and range 4 meters. The comparison plot presents the outlined measures of performance, presented as ratios with respect to the corresponding values of the baseline system.

The performance improvement of the motion alternatives in Figure 3 results from a number of its beneficial characteristics, featured in Table 1. In particular, the motions in this set have non-uniform sampling of arc length. The arcs with higher curvature are shorter, resulting in lower heading change. High curvature arcs are particularly helpful in difficult environments. This feature allows the rover to maneuver in such environments using smaller steps. In addition, the sampling of curvature is non-uniform as well. There are more arcs with curvature near zero to allow avoiding sparse obstacles with minimal deviation off-course.

| Arc Set Parameter | Value | Explanation |
|---|---|---|
| Number of arcs | Increase | This parameter offers a trade-off between navigation quality and computational complexity. At the cost of the extra computation, increasing the number of arcs increases the likelihood of successful traversal of rough terrain and complex environments. It also is likely to reduce the distance traveled and energy expenditure. |
| | Decrease | Decreasing the number of arcs can save computation by evaluating fewer motion alternatives. This will lead to a reduction in the time of traversal. However, typically this reduction is not large, since the time-complexity of rover navigation is dominated by other tasks, such as perception and state estimation. |
| Maximum curvature | Increase | We found that it is beneficial to use the highest available value of maximum curvature of paths, assuming arc length is chosen appropriately (see below). This value is usually upper-bounded by the mobility hardware of the rover. |
| Max. arc length | Increase | A greater length of arcs in an arc set can greatly reduce the time of traversal in benign terrain with sparse obstacles. Traveling a greater distance between re-evaluating perception information and state estimation, and replanning allows saving time, since these processes dominate time-complexity of navigation. Distance traveled and energy expenditure are also likely to be reduced when increasing the lengths of arcs in benign terrain (while maintaining appropriate maximum heading change, see below), especially if a greater number of arcs is used. However, in rough terrain with dense obstacles, longer arcs are likely to become more costly in all measures of performance due to the reduced likelihood of at least one arc avoiding all obstacles. |
| | Decrease | A reduced length of arcs is particularly suited for rough terrain. It increases the time duration of traversal, but it lowers the risk of failure to traverse the environment. It was not noted to have a significant effect of the distance traversed. An small increase in energy expenditure was noted due to increased wheel steering at arc transitions. |
| Max. heading change | Increase | The length of constant-curvature arcs and their heading change are coupled. Hence, insofar as the maximum heading change affects the maximum arc length, the discussion above applies. However, it is worth noting that increasing this parameter (up to a certain value) has a general effect of increasing the likelihood of successful traversal in rough terrain. A good value determined experimentally was 90º. Beyond that, no significant benefit was noted, and all performance measures appeared to degrade slightly. |
| | Decrease | Reducing the value of this parameter resulted in reduction of navigation time efficiency in experiments. |
| Arc length sampling | Uniform | Best experimental results were obtained by cropping the length or arcs to satisfy the chosen maximum heading constraint. |
| Curvature sampling | Non-uniform | Choosing uniform curvature samples in the range between zero and maximum curvature yielded good results. However, traversal distance and energy expenditure were visibly improved by sampling more densely at lower values of curvature. |

Table 1. General principles of designing sets of arc motion alternatives for improved rover navigation.

*Improving Performance with Variable Curvature Primitives*

Through tuning the parameters of a set of arc motion alternatives, a visible improvement in performance can be obtained. However, a further improvement was noted by augmenting the set of arcs with the paths of variable curvature. These paths can be designed to have the same ($x,y$) end-points as the arcs, yet arrive at different headings. Moreover, these paths need not even coincide with arc endpoints. Experimentally, it was found that utilizing such additional paths results in a significantly greater variety of motions considered during navigation, which was shown to boost the likelihood of finding an obstacle-free path in rough terrain. Further, in a loose sense, by allowing variable curvature, the maneuverability of the vehicle was exploited to a greater degree. For example, in this setting maximum curvature of the robot's mobility system can be utilized by a greater number of motion alternatives than in the case of a set of arcs.

The present scheme of designing motion alternatives is also governed by a choice of parameters. It inherits most of the same considerations as the design of arc sets, while it also introduces additional considerations. These considerations include whether or not the variable curvature motions are used in conjunction with arcs or by themselves, whether

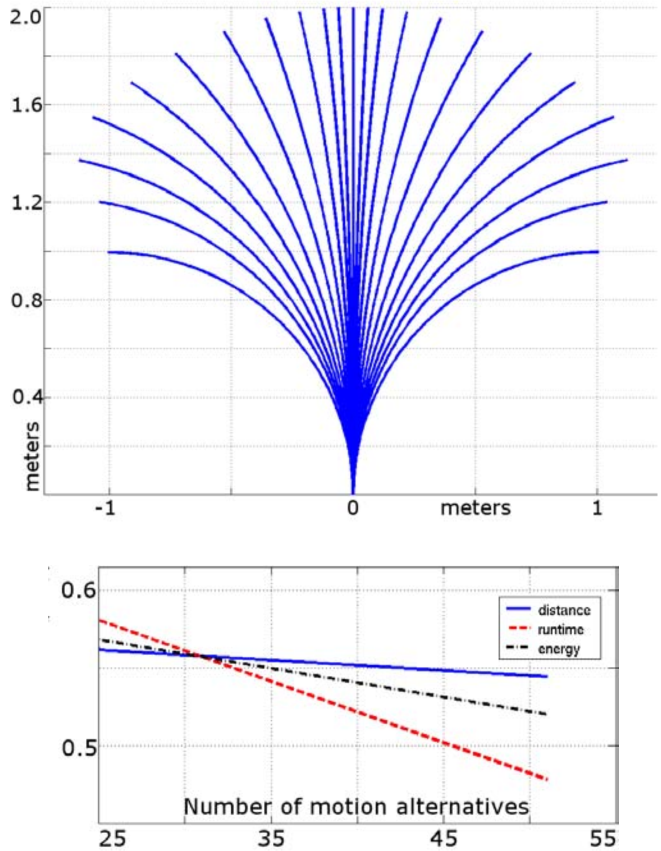


**Figure 3.** Top: a set of arc motion alternatives designed for improved rover navigation performance. Note that some of the design principles outlined above are featured by this example, including reduced maximum heading change and irregular sampling of curvature. Bottom: the plot depicts the measured performance improvement of this set of motions. It allows the reduction of the cost (distance, run-time, or energy) of rover navigation by 30-40% with respect to the baseline set of arcs.

their endpoints coincide, and if so, what are the headings of the coincident end-points. However, unlike the parameters governing the construction of arc sets, these additional considerations did not appear to have a significant effect on the experimental performance measures of navigation. Best results have been obtained by using sets of motion alternatives consisting of arcs and variable curvature curves in equal ratio; their end-points were allowed to coincide at three different headings: -90º, 0º, and 90º. A greater number of different headings at coincidence points did not appear to yield a notable performance improvement.

In order to generate the set of motion alternatives described here, it is necessary to find trajectories of the robot that guide it from a given initial state to an arbitrary final state (in particular, $x$, $y$, and heading). Since this is a non-trivial problem for complex kinematics systems such as rovers, a boundary value problem solver by Howard and Kelly [4] was utilized. With this solver, it was possible to generate and evaluate sets of motion alternatives with variable curvature paths arranged in arbitrary patterns. The motions were represented as *clothoid* curves, where curvature was a polynomial parameterized by path length.

The top of Figure 4 shows a set of motion alternatives by following the design outlined above. The bottom of the figure shows a plot of the navigation performance measures, similarly presented as ratios with respect to the baseline system. As can be seen, the plot demonstrates a notable, factor-of-two, improvement over the control sets consisting of solely arcs, even after careful optimization. This performance boost can be attributed to a greater variety of paths in a control set that contains a significant number of variable curvature motions. Similar to the set of motions in Figure 3, this control set features non-uniform sampling of arc length and curvature; the resulting benefits are described in the previous subsection. Furthermore, the introduction of variable curvature motions allows greater flexibility in navigating difficult environments. It leads to utilizing near-maximum curvature more frequently than only twice, as in the case of constant curvature arcs (namely, for the arcs to the left and right).

## 5. CONCLUSION

The paper focused on improving autonomous rover navigation by carefully redesigning an important component of conventional rover navigation systems, the process of selecting the immediate motions of the rover. Through no other change but the choice of motion alternatives considered by this process, a significant performance improvement was attained. Relevant performance measures have been developed that allowed the quantification of the benefit of this contribution. Through this analysis, it was determined that the enhanced rover navigation system presented here offers visible advantages over the popular Mars rover navigation solutions.

The software produced in this work has been integrated with the CLARAty [8] software architecture and tested on a relevant platform (FIDO rover prototype) at the JPL Mars Yard. In the future, we plan to seek opportunities for evaluating the technology in rover missions as well as terrestrial applications in order to enable future systems to benefit from this research.

## ACKNOWLEDGMENTS

This work was sponsored by the Caltech Jet Propulsion Laboratory as part of the Director's Research and Development Fund program. We also acknowledge our collaboration with Ross Knepper, Colin Green, and Thomas Howard.

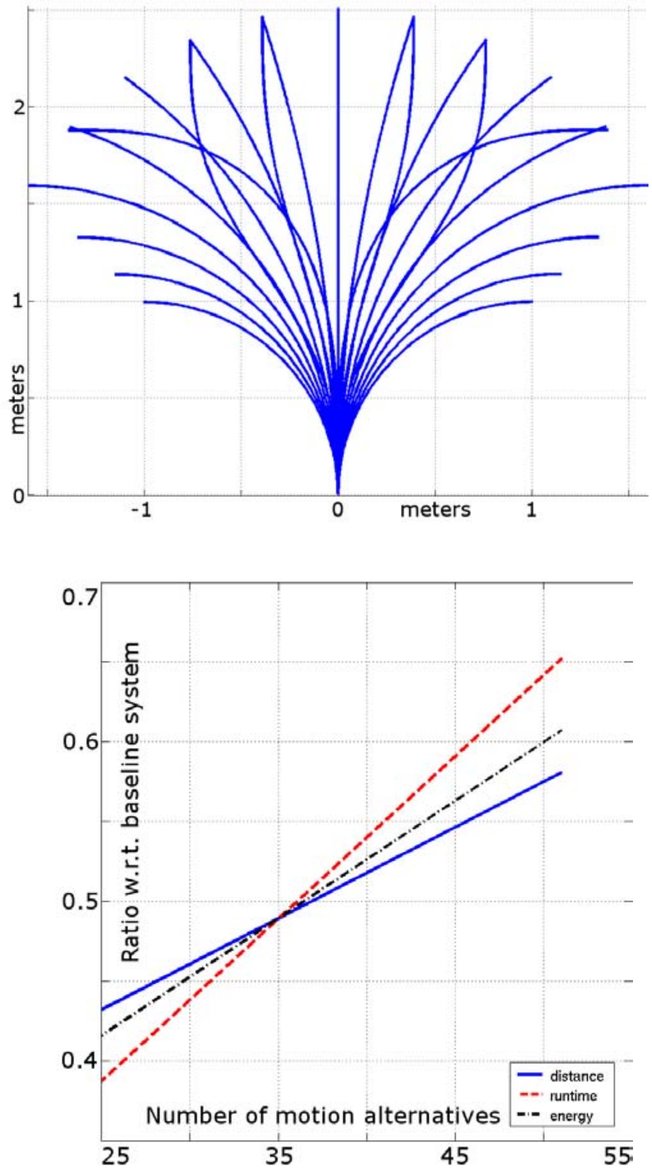


**Figure 4.** Top: a set of motion alternatives that features variable curvature paths along with arcs. Path sets such as this have been shown experimentally to improve the performance of rover navigation. Bottom: the plot presents the comparison of performance of this set of paths versus the baseline system. All three performance metrics exhibit approximately factor of two improvement over the baseline.

## REFERENCES

[1] J. Carsten, A. Rankin, D. Ferguson and A. Stentz, “Global path planning on board the Mars Exploration Rovers”, in *Proc. of the IEEE Aerospace Conference*, 2007.

[2] S. Goldberg, M. Maimone and L. Matthies, “Stereo vision and rover navigation software for planetary exploration”, in *Proc. of the IEEE Aerospace Conference*, 2002.

[3] C. Green and A. Kelly, “Toward Optimal Sampling in the Space of Paths,” in *Proc. of the Int. Symp. of Robotics Research*, 2007.

[4] T.M. Howard and A. Kelly, “Optimal rough terrain trajectory generator for wheeled mobile robots”, *International Journal of Robotics Research*, 26(2):141-166, 2007.

[5] A. Kelly, “An Intelligent Predictive Control Approach to the High Speed Cross Country Autonomous Navigation Problem”, Ph.D. Dissertation.

[6] R. Knepper and M. Mason, “Empirical Sampling of Path Sets for Local Area Motion Planning,” in *Proc. of the Int. Symp. on Experimental Robotics*, 2008.

[7] M. Maimone, C. Leger and J. Biesiadecki, “Overview of the Mars Exploration Rovers' autonomous mobility and vision capabilities”, in *Proc. of the IEEE Int. Conf on Robotics and Automation*, 2007.

[8] I.A. Nesnas, "CLARAty: A Collaborative Software for Advancing Robotic Technologies," *NASA Science and Technology Conference,* University of Maryland University College, Adelphi, MD, June 2007.

[9] R. Simmons, L. Henriksen, L. Chrisman and G. Whelan, “Obstacle Avoidance and Safeguarding for a Lunar Rover,” in *Proc. of the AlAA Forum on Advanced Developments in Space Robotics*, 1998.

[10] A. Stentz and M. Hebert, “A Complete Navigation System for Goal Acquisition in Unknown Environments”, in *Proc. of the IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*, pp. 425—432, August 1995.

## BIOGRAPHY

Mihail Pivtoraiko is a Ph.D. student at the Robotics Institute at Carnegie Mellon University. He has over four years of experience in off-road robot motion planning and navigation, and has participated in DARPA projects (PerceptOR, LAGR), as well as the Mars Technology Program project with the Caltech Jet Propulsion Laboratory (JPL). He has two years of experience working with JPL prototype rovers, including validation of navigation algorithms in JPL Mars Yard.

Issa Nesnas is a Group Supervisor for the Robotic Software Systems group at the Caltech Jet Propulsion Laboratory. He has over 16 years of experience in robotic system and software design, sensor-based robotic control, and vision-guided manipulation. Issa joined JPL in 1997, where he worked on planetary dexterous manipulation for rovers and landers. He developed algorithms for vision-based manipulation, sample acquisition, and instrument placement from rover platforms.

Alonzo Kelly is Associate Professor of Robotics at the Robotics Institute of Carnegie Mellon University. He has been active in robotics in academic, industrial, space, and military sectors for 25 years. His research interests include control, state estimation, perception, motion planning, simulation, and human interfaces for indoor and outdoor mobile robots.